Uranus & Neptune: Formation, Evolution, and Interior Structure in Solar and Extrasolar Systems

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Sep. 7 2012
Our goal: improve our understanding of low-mass planets

Why? (1) Planetary interiors are the key for understanding the formation of planetary systems. (2) Planetary composition teaches us about the physical properties of the solar nebula.

Uranus and Neptune are the Super-Earths/Mini-Neptunes of the Solar System
Observational Constraints for Interior Modeling:

- Mass
- Radius (usually equatorial)
- Angular velocity $\omega$
- Gravitational Moments (up to $J_6$)
- 1 bar Temperature
- He/H ratio in the atmosphere

- What about magnetic field, moment of inertia, shape?
The external gravitational potential of a planet

\[ U = \frac{GM}{r} \left( 1 - \sum_{n=1}^{\infty} \left( \frac{a}{r} \right)^{2n} J_{2n} P_{2n} (\cos \theta) \right) + \frac{1}{2} \omega^2 r^2 \sin^2 \theta. \]

with GM and \( J_{2n} \) constrain the interior density:

\[ M = \iiint \rho(r, \theta) d^3 \tau, \]
\[ J_{2i} = -\frac{1}{MR_{\text{eq}}^2} \iiint \rho(r, \theta) r^{2i} P_{2i}(\cos \theta) d^3 \tau. \]

\( d\tau \) is a volume element - the integrals are performed over the entire planetary volume.
Uranus and Neptune
the “Icy (?) Planets”

Uranus: $14.5 \, M_\oplus @ 19.2 \, \text{AU}$
Neptune: $17.1 \, M_\oplus @ 30 \, \text{AU}$

“Standard” Composition: rocks, ices, and H/He atmosphere

**Similarities:** Mass, Radius, Rotation, Radial Distance

**Differences:** Heat Flux, Atmospheric Enrichment, Tilt, Satellite System
Uranus and Neptune

For Uranus and Neptune only $J_2$ and $J_4$ are available

- **Standard models:**
  - Inner region: rocky core ~ 25%
  - Ices (mostly $\text{H}_2\text{O}$) ~ 60-70%
  - $H$ and $He$ atmosphere ~ 5-15%

A large range of possible internal structures ➔ composition is unknown
An ice layer is not needed. A continuous increase in the hydrogen mass fraction with increasing radius gives a good fit to the moments.

Uranus and Neptune

The gravity data is **insufficient** to constrain the planetary composition

Are Uranus and Neptune icy?


Reasons to believe they have water:
(1) Magnetic fields – *is it really?*
(2) Water is abundant at these distances – *what about Pluto?*
The Rotation Periods of Uranus and Neptune

- What are the rotation periods of Uranus and Neptune?
  - Complex multipolar nature of magnetic fields
  - Where are the magnetic fields generated?

Rotation period is important because it is used by interior models.
Zonal wind velocities for geoids and solid body rotation rates that minimize the dynamical heights and modified shapes.

U: 17.24h $\Rightarrow$ 16.58h; N: 16.11h $\Rightarrow$ 17.46hs

**Uranus**: $P \sim 16.58h$ (V: 17.24h)

**Neptune**: $P \sim 17.46h$ (V: 16.11h)

Helled et al., 2010, *Icarus*, 210, 446
black/gray lines - Voyager rotation periods
blue/turquoise lines - modified rotation periods (Helled et al., 2010)

Mass fraction of metals in the outer envelope ($Z_1$) and in the inner envelope ($Z_2$) 3-layer models of Uranus and Neptune
Nettelmann, Helled, Fortney, Redmer, PSS, 2012
Interior models with modified rotation

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Maybe Uranus and Neptune are **not** “twin-planets”

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Giant impacts: tilt and internal flux

- Uranus is tilted and has very low internal flux – are these two connected??

Neptune: Radial Collision

- Enough energy to mix the Core: Mixed and adiabatic interior, efficient cooling

Uranus: Oblique Collision

- Angular momentum deposition: Core, convection is inhibited → slow cooling, tilt

Uranus and Neptune

Important for understanding extrasolar planets in this mass regime!
• What are Uranus and Neptune made of? Are they Icy? Can we neglect planetary evolution (e.g., mixing, impacts)?

• What can we really say about low-mass exoplanets? Is it reasonable to assume adiabaticity?

Stop scaling our solar system planets!
Thank you!